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Technical Report 171

EVALUATION OF MULTIPORT FIBER-OPTIC BUNDLE COUPLERS

DE Altman
TA Meador

28 October 1977

Test and Evaluation, 1 July 1976 to 30 September 1977

Prepared for
NAVAL AIR SYSTEMS COMMAND
Washington, DC 20360

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Development and evaluation of fiber-optic coupling devices are discussed.

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INTRODUCTION

This effort was carried out as part of the Fiber-Optic Device Technology Program, the purpose of which is to develop and evaluate the feasibility and practicability of Naval fiber-optic technology. The goal has been to evaluate the performance of multiport fiber-optic couplers designed for use with multifilament fiber bundles in data-bus systems. The results obtained are to be used to identify further tasks required for coupler development. Such tasks will be carried out under the Fiber-Optic Device Technology and Manufacturing Technology programs.

BACKGROUND

Military data-bus technology has been developed to fulfill platform operational requirements for increased maneuverability, survivability, reliability, and maintainability. The fundamental approach is to use a single common transmission path, called a bus, for most signal transfer within an electronic system. Use of the bus is obtained by system equipments through terminals which perform signal conversion, message processing, and traffic monitoring. Terminals obtain access to the bus by means of couplers. A coupler diverts a portion of the signal power present on the bus to the terminal and directs signal power originating at the terminal onto the bus.

Research, development, and operational experience have been combined to codify aircraft data-bus technology resulting in the promulgation of two standards, MIL-STD-1553A and MIL-G-85013. Surface-platform data-bus technology is being developed through tl Shipboard Data Multiplex System (SDMS) program under NAVSEA sponsorship. The aircraft standards and the evolving shipboard system utilize wire-guided communications. On aircraft the use of shielded twisted-pair cable is specified and the SDMS uses coaxial cable.

Wire transmission is vulnerable to disruption by electromagnetic interference from such sources as switching equipment, transmitters, lightning strikes, or a nuclear electromagnetic pulse. On the other hand, glass fibers are transmissive only in the optical portion of the electromagnetic spectrum and are insensitive to radiation at lower frequencies. Thus, a system employing fiber-optic technology should enjoy a higher degree of immunity to electromagnetic interference than one utilizing metallic transmission.

Two fundamental configurations are noteworthy in fiber-optic data-bus design[1,2]. One, the serially tapped bus, is based upon the allocation of a dedicated coupler to each terminal. Each coupler, analogous to a coaxial tee, is spliced into the data bus near the terminal it serves. As with a similarly constructed wire bus, the end-to-end loss of such a system of cascaded lossy components increases exponentially with the number of couplers. The second configuration, the star, or radial-arm bus, uses a single multiport coupler which is shared by, and connected directly to all terminals. The multiport coupler represents a single lumped loss which increases linearly with the number of terminals. Thus, a bus of many terminals will have a much lower loss when built with the multiport coupler.

---

[1] Milton, AF, and Brown, LW, Nonreciprocal Access to Multiterminal Optical Data Highways, IEEE/OSA CLEA, Washington, DC, May 1973

[2] Hudson, MC, and Thiel, FL, Applied Optics, 13, 2540, 1974

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MULTIPORT COUPLER OPERATION

The multiport coupler accepts optical power from any input terminal connected to it and distributes that power equally among all output terminals. Typically, a multiport coupler consists of a scrambling block and connecting waveguides as shown in figure 1a. These parts are assembled and placed in a housing which provides access to the connecting waveguides through connectors to which terminated fiber bundles are attached. The bundles extend between the coupler and the terminals.

Optical power travels through a cable to the coupler where it enters a connecting waveguide. Because of the nature of the optical power source and the fiber-optic bundles, the spatial characteristics of the power entering the waveguide can be approximated by a cone of light. The cone of light in figure 1a leaving any waveguide on the left side of the block spreads across the cross-section of the block and over all the waveguides on the right. The maximum input-cone angle that will experience total internal reflection at the side surface of the block is determined by the refractive index difference at this boundary. Figure 1b shows a variation of the multiport coupler represented in figure 1a. A mirrored surface on the right-hand side of the mixing block directs the optical power back toward the left-hand side where it entered. In this configuration, the input waveguides also serve as output waveguides.

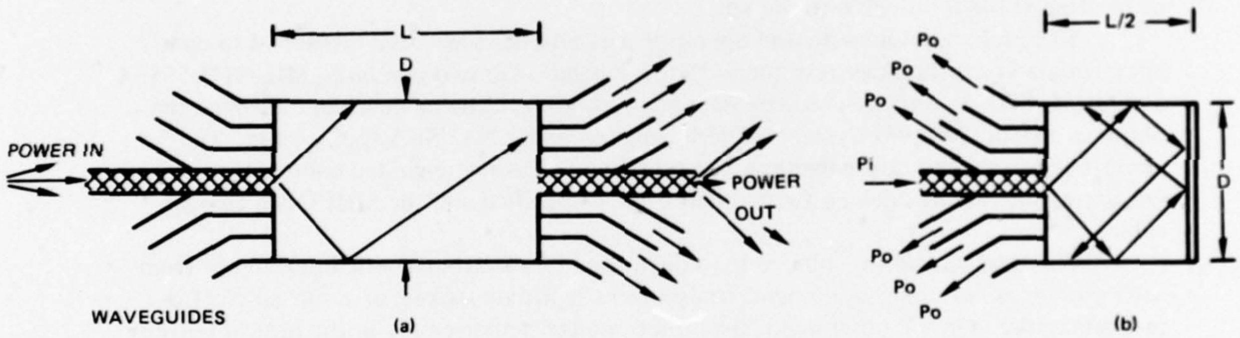

Figure 1. Coupler operation.

Previous discussions of multiport coupler theory have shown that for efficient operaation, a coupler must match or exceed the numerical aperture (NA) of the connecting fiber bundles and that the cross sectional area of the scrambling block must equal the sum of the cross sectional areas of the connecting fiber bundles. The NAs of the bundles, waveguides, and scrambling block are determined by the difference of the indices of refraction of their core (N_{core}) and cladding (N_{clad}) materials. In particular, the limiting NA is

$$NA = (N_{core}^2 - N_{clad}^2)^{1/2} \quad (1)$$

so that the waveguides and block will internally reflect light rays entering at angles (θ) to their axes of up to

$$\theta_{max} = \sin^{-1}(NA) \quad (2)$$

The optical power entering the scrambling block within θ_{max} will fan out until reflected at the core/clad interface. In so doing, it will spread over the cross sectional area of the block which, to conserve power, must equal the sum of the areas of the data-bus bundles. Thus, the maximum cross sectional dimension, D, and the minimum length, L, of the optical path in the scrambling block are determinable. In the reflective coupler of figure 1b, D will be of the same magnitude as in figure 1a. However, L need only be half the value of L in figure 1a since the optical power will traverse the length twice. Distribution of the optical power over the output ports of a coupler should be uniform to equalize the power levels at all terminals under all transmission conditions. Thus, the length, L, of the mixing block must be adequate. Milton[3] and Biard[4] have reported the necessary relationship between L, D, and NA. Milton[5] has shown that the distributed optical power will vary in intensity over the surface of distribution as an empirical function of $[(L/D)\tan(\theta_{max})]$. Biard[6] has derived an expression for the relationship of L, D, scrambling block core index, and a specific distribution of input optical power which will distribute power uniformly over the output surface of the block:

$$\frac{L}{D} = \frac{(N^2 - NA^2)^{1/2}}{NA} \tag{3}$$

where

L = scrambling-block length

D = scrambling-block cross-sectional dimension

N = scrambling-block index of refraction

NA = numerical aperture of optical power entering the scrambling block

The significance of this expression is that coupler scrambling-block dimensions and coupler operation are dependent upon fixed characteristics of the fiber-optic bundles with which a coupler is to be used, and that employing a given coupler with different bundles may give a different coupler performance.

Performance of a multiport coupler can be specified by the level of optical power available at all output ports relative to the level of input power. Ideally, the only decrease in level should result from power division in the coupler, that is:

$$P_{o,j} = \left(\frac{1}{N}\right) P_{i,k} \tag{4}$$

where

Po, j = Power available at output port j

N = number of output ports

Pi, k = power input at port k

This performance is never attained because factors other than division loss cause attenuation of optical power within the coupler. Chief among these factors are reflections, losses at the

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[3]Milton, AF, and Lee, AB, Applied Optics, 15, 244 (1976)

[4]Biard, JR, and Shaunfield, JE, Optical Couplers, AFAL-TR-74-314, December 1974

[5]Milton, op cit, p 248

[6]Biard, op cit, p 71

core/clad interface, and cross-sectional area misalignment caused by necessary mechanical tolerances. Multiport coupler performance can be described by the following:

$$T = \frac{(Po, j)k}{Pi, k} \quad \text{transmission between any two ports} \tag{5a}$$

$$T^* = \frac{\Sigma(Po, j)k}{Pi, k} \quad \text{total transmission of the coupler} \tag{5b}$$

$$V = \frac{(Po, j)k}{(Po, j)\ell} \quad \text{port-to-port transmission variation} \tag{5c}$$

where

$(Po, j)k$ = power exiting any port j with power input at any other port k

Pi, k = power input at port k

$\Sigma(Po, j)k$ = power exiting all ports save input port k

$\frac{(Po, j)k}{(Po, j)\ell}$ = ratio of output power at any one port j with power input at port k to power output at port j with power input at port ℓ

These ratios provide a means of specifying device performance. They also enable one to compare diverse coupler designs.

COUPLER PROCUREMENT AND TESTING

For the purposes of procurement and testing, the following fiber-optic cable characteristics were specified:

- Fiber cable to consist of a jacketed bundle of fibers
- Fibers to have step refractive-index profile
- $0.6 \geq NA \geq 0.5$ at all wavelengths between 8000Å and 9500Å
- Fibers to be of glass composition
- Fiber diameters to lie within the range $0.002 \leq$ diameter ≤ 0.005 inch
- Number of fibers sufficient to fill a cross-sectional circular area with diameter 0.047 inch
- Fiber optical attenuation to be less than 600 dB/km at all wavelengths between 8000Å and 9500Å

The following types and quantities of couplers were procured from Spectronics, Incorporated:

- eight 6-port couplers
- four 9-port couplers

- two 16-port couplers

The coupler types are shown in figure 2.

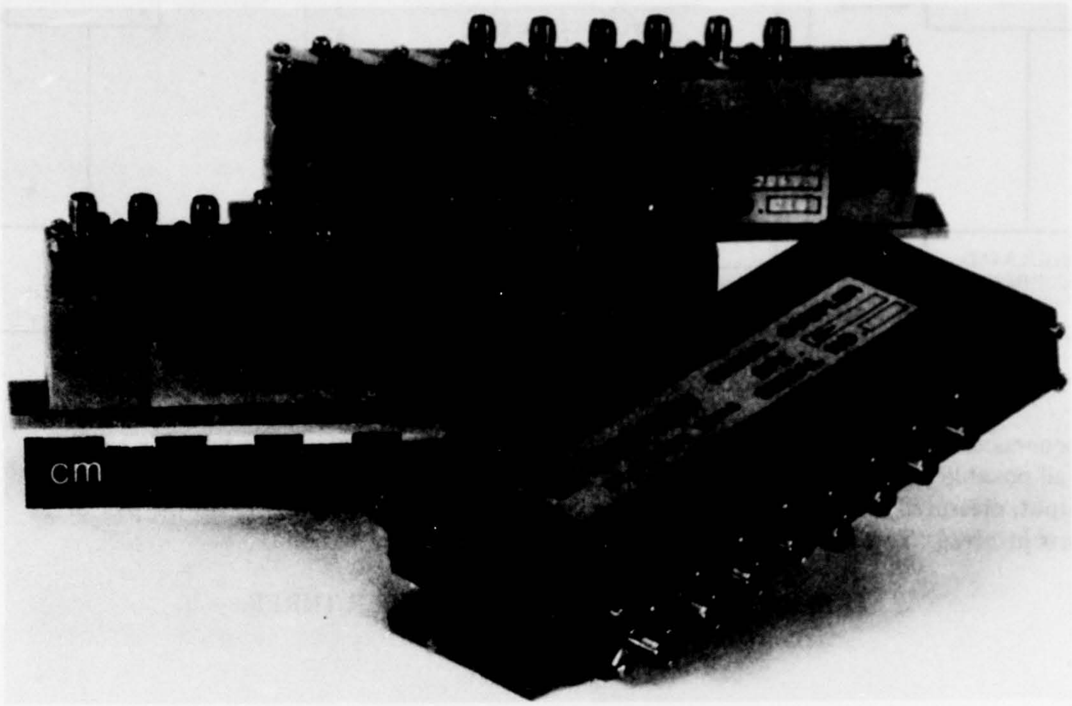

Figure 2. Multiport couplers.

The couplers were tested with two 15-metre sections of fiber cable, fabricated by American Optical Company. Bundle numerical aperture was measured at 0.5, bundle loss was measured at 390 dB/km at 8500Å. The cables were terminated at either end with ferrules, Sealectro Corporation part 55-907-0149-89. Ferrule inside diameter was nominally 0.045 inch. One bundle-end was illuminated by a current-regulated tungsten lamp. An image of the rectangular emitting area of the lamp was focused on the end of the bundle using a pair of short focal length lenses capable of exceeding the NA of the bundle. A stop between the lenses and the fiber bundle limited the NA of the illumination to that specified. Since the image of the lamp radiating area was larger than the bundle diameter, the spatial aperture of the bundle was also filled. Interposed between the condensing and focusing lenses was an interference filter to limit the test spectrum to the specified range.

One end of the other bundle was positioned coaxially with a 1-cm diameter PIN photodiode. A load resistor was connected across the diode and a microvoltmeter was used to measure the resultant voltage. The diode was not reverse biased, but was operated in the photovoltaic mode to give the most linear relation between output voltage and input optical power. Figure 3 illustrates the test setup.

Testing of each coupler was initiated by connecting the two free ends of the fiber-optic cables through the splice connector which aligned them in a butt joint. Butting the ends established a zero loss reference. After determination of the zero loss reference the two ends were

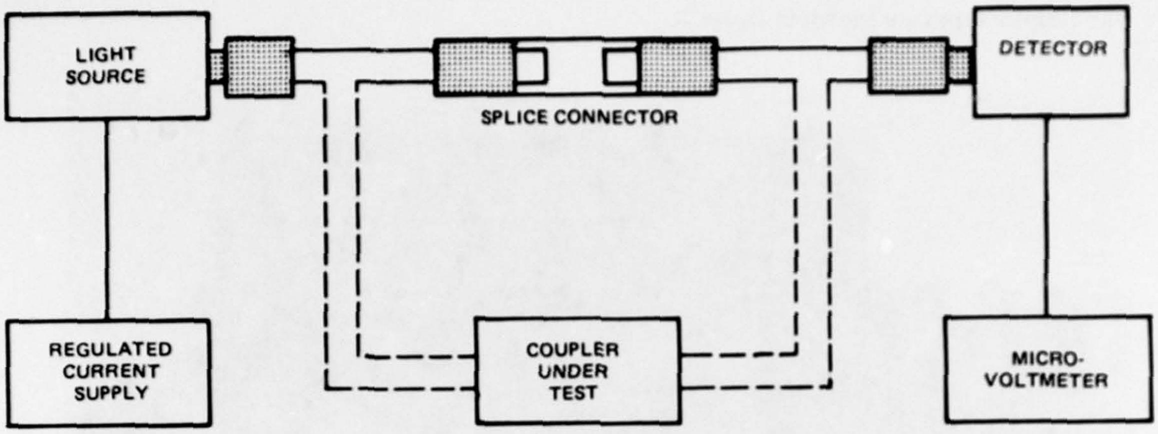

Figure 3. Coupler loss-measuring setup.

disconnected from the splice connector and connected to the coupler to be tested in each of all possible input/output port combinations. The ratio of the reference level to the coupler output, measured at a port, was taken as the coupler transmission factor, T, for the pair of ports involved. Test results for a nine port coupler are shown in table 1.

TABLE 1. DATA FOR COUPLER NUMBER THREE.

Output Ports

Input Ports	1	2	3	4	5	6	7	8	9	T*
1	-	.040	.042	.035	.042	.038	.041	.047	.039	.328
2	.046	-	.039	.040	.043	.040	.041	.043	.036	.328
3	.042	.040	-	.034	.040	.035	.035	.042	.046	.304
4	.041	.041	.030	-	.035	.034	.035	.038	.031	.285
5	.041	.040	.036	.031	-	.038	.037	.043	.036	.302
6	.042	.040	.035	.032	.040	-	.028	.042	.034	.293
7	.041	.040	.034	.034	.039	.033	-	.033	.031	.290
8	.050	.044	.044	.040	.046	.042	.030	-	.039	.335
9	.039	.038	.034	.030	.039	.034	.032	.039	-	.285
V	.78	.86	.68	.75	.76	.78	.68	.81	.67	-

The input ports are listed in the left hand column while output ports are listed in the top row. The tabulated numbers are the transmission factor, T, measured between ports. T*, the total transmission of the coupler is in the far right hand column. V, on the bottom row, is the port-to-port transmission variation, and represents the optical-signal range from successive input ports. Data for all couplers are found in Appendix A. Table 2 summarizes the average T, T*, and V_{max} for all couplers. Also included is $V_{coupler}$ determined by the maximum and minimum T's of the coupler.

TABLE 2. SUMMARY OF COUPLER PERFORMANCE DATA.

Coupler Serial No	No of Ports	T_{max}	T_{min}	T_{avg}	T^*_{avg}	V_{max}	$V_{coupler}$
1	16	.0223	.0095	.0158	.237	.53	.43
2	16	.0250	.0035	.0171	.257	.48	.34
3	9	.050	.028	.038	.305	.67	.60
4	9	.052	.032	.039	.312	.74	.61
6	9	.036	.017	.026	.210	.54	.47
10	9	.036	.010	.0257	.206	.33	.27
7	6	.074	.043	.059	.294	.68	.58
8	6	.062	.037	.043	.241	.74	.65
9	6	.057	.031	.046	.230	.58	.51
11	6	.073	.032	.047	.236	.51	.44
12	6	.045	.026	.039	.193	.60	.58
13	6	.055	.032	.045	.223	.68	.58
14	6	.058	.036	.046	.233	.75	.62
15	6	.068	.047	.058	.288	.75	.69

Table 2 shows a wide variation in performance within all groups of couplers. For instance, in the group of 9-port couplers, the best and worst values of T_{avg} were 0.038 and 0.0257. Ideally, these devices should exhibit values given by equation (4). In this case,

$$T = \frac{Po, j}{Pi, k} = \frac{1}{9} = 0.11 \tag{6}$$

The deviation of actual coupler performance from this value can be explained by considering the construction details of these particular devices. Figure 4 shows the essential parts of a 9-port Spectronics coupler. The rectangular scrambling block has rectangular waveguides attached to one face and a reflecting silver composition deposited upon the opposing face as shown in figure 4. The block and waveguides are all of square cross-section, are composed of the same material, and are clad with the same material. The waveguides are pieced together from two perpendicular sections joined by a prism with one face mirrored as in figure 4. Each is of such cross-sectional dimension as to circumscribe the circularly terminated bundle as in figure 4. Optical power enters the coupler through one waveguide where it is redirected by the silvered prism toward the scrambling block. In the block, the direction of the power is reversed by the mirrored surface and spreads over all the waveguides. Within the coupler, attenuation of the power results from propagation through interfaces where index discontinuities exist, at the waveguide/cable, and the waveguide/prism interfaces, and where the power is reflected at the mirrored surfaces.

Transmission through the interfaces is given by

$$T = (1-R) \tag{7}$$

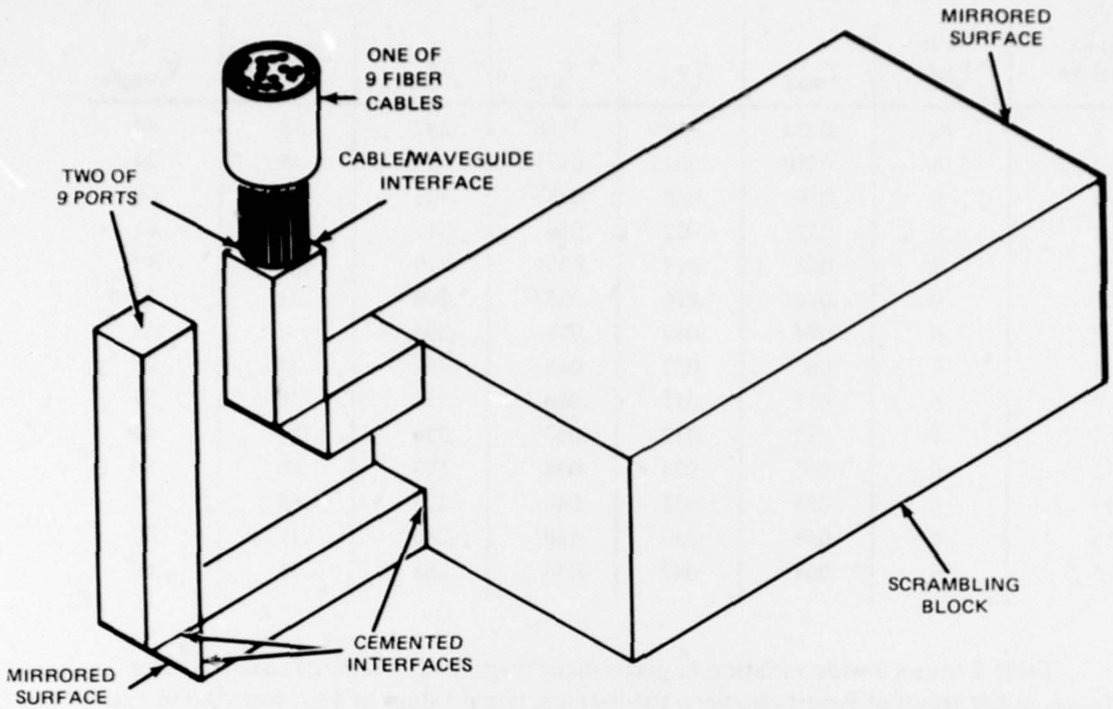

Figure 4. Nine-port coupler construction showing two of the nine waveguides in place.

where R, the coefficient of reflectivity, is given for normal incidence by,

$$R = \left(\frac{N_2 - N_1}{N_2 + N_1}\right)^2 \tag{8}$$

and N_2 and N_1 are the indices of refraction of the adjacent media. For the materials used, R of the waveguide/cable interface is 0.056, R of the waveguide/prism interface is 0.002, and R of the waveguide/scrambling block interface is negligible. Now an expression for transmission within the coupler can be given as

$$T_1 = T_2^2 \; T_3^4 \; R_m^3 \tag{9}$$

where

T_1 is transmission from coupler input port to coupler output port

T_2 is transmission through waveguide/cable interface

T_3 is transmission through waveguide/prism interface

R_m is mirrored surface reflectivity, here 0.96

and, for the values given,

$$T_1 = (1-0.056)^2 \;\; (1-0.002)^4 \;\; (.96)^3 = 0.782$$

Additional loss is incurred at the waveguide/cable interface where the area mismatch pictured in figure 4 fails to couple all of the exiting optical power into the circular cable. Assuming uniform density of optical power across the waveguide, the resultant transmission factor can be expressed as a ratio between the cross-sectional areas of the fiber bundle and waveguide, ie,

$$C = \frac{\pi r^2}{(2r)^2} = \frac{\pi}{4}$$

The transmission from input to output through the couplers can be expressed as:

$$T = T_1 \cdot C \cdot 1/N \tag{10}$$

For the 16-port coupler,

$$T = (0.782)\left(\frac{\pi}{4}\right)(0.0625) = 0.0384$$

for the 9-port coupler,

$$T = (0.782)\left(\frac{\pi}{4}\right)(0.111) = 0.0682$$

and, for the 6-port coupler,

$$T = (0.782)\left(\frac{\pi}{4}\right)(0.167) = 0.102$$

Thus, the performances indicated in table 2 fall below those predicted by equation (10) for the couplers. The mechanisms probably responsible for the unpredicted loss include:

- Surface imperfections on the scrambling block and waveguides
- Mechanical tolerance buildup
- Lack of control of the refractive index of the adhesive used in joining waveguides, prisms, and scrambling block
- Inclusion of opaque matter in the cladding material which was observed to have flowed over the end of the waveguides of the connector/waveguide interface
- Absorption in the glass and cladding material

The port-to-port transmission variation, V, expresses the fact that each of the above loss mechanisms can apply to a different degree to each port-to-port path through the coupler. Measurement of the individual loss mechanisms can only be performed during coupler assembly and was beyond the scope of this investigation.

Another feature of the couplers, related to the variation, V, is the nonreciprocity of Ts between some ports. The nonreciprocity may possibly arise from variations in transmission-path characteristics caused by the factors discussed above. The nonuniformity of path characteristics would cause the spatial characteristics of the optical power to vary which, in turn, would effect a variation in performance as pointed out in the discussion of coupler operation.

CONCLUSIONS

The evaluation effort described in this report has focused upon multiport fiber-optic couplers designed for use with multifilament fiber-optic bundles. Moderate deviation from expected performance has been noted, eg, measured transmission of each coupler has fallen below that predicted, and wide variation in port-to-port transmission, T, has been noted. A convenient method of summarizing the results and comparing them with predicted performance is to consider T_{avg} in table 2 and T of equation (10) as

$$T\ (dB)\ coupler = 10 \times \log_{10} (T_{avg})$$

and

$$T\ (dB)\ predicted = 10 \times \log_{10} (T)$$

V_{max} can also be so considered, and

$$V\ (dB) = -(10 \times \log V_{max})$$

These give T(dB) as a negative value, indicative of transmission loss, and V(dB) as a dynamic range. The results are summarized in table 3.

TABLE 3. TEST RESULTS.

Coupler Serial Number	Number of Ports	T(dB) Measured	T(dB) Predicted	V(dB)
1	16	-18	-14.2	2.7
2	16	-17.6	-14.2	3.1
3	9	-14.2	-11.7	1.7
4	9	-14.0	-11.7	1.3
6	9	-15.8	-11.7	2.6
10	9	-15.9	-11.7	4.8
7	6	-12.3	- 9.9	1.6
8	6	-13.1	- 9.9	1.3
9	6	-13.3	- 9.9	2.3
12	6	-13.2	- 9.9	2.9
12	6	-14.0	- 9.9	2.2
13	6	-13.4	- 9.9	1.6
14	6	-13.3	- 9.9	1.2
15	6	-12.3	- 9.9	1.2

The feasibility of the concept represented by the evaluated couplers is clear: the predicted transmission performance has been approached; performance improvement can probably be obtained by development of precision manufacturing methods; the couplers are manufacturable and available for system evaluation.

OBSERVATIONS

Four observations were made during the evaluation:

1. The connectors to which the fiber cables attached were brass and subject to shaving by the stainless steel ferrules on the cables. The shavings were deposited upon the outward looking face of the connecting waveguides resulting in a decrease in light transmission. Correction of this condition required disassembly of the couplers to clean the waveguide faces.

2. During cleaning of the faces, it was noticed that the compound used to clad the waveguides had flowed over the faces of many of the waveguides. Debris had been trapped in the overflow which had solidified.

3. Some of the solvents used to clean the faces of the waveguides attacked the cladding material leaving pits in it adjacent to the faces of the waveguides.

4. The cable ferrules could be modified to provide a square termination for the cable fibers. This would eliminate the $\pi/4$ loss factor in equation (10) and result in an increase in T of 1 dB. It would also require a keyed connector.

RECOMMENDATIONS

The following recommendations are made:

1. Analysis of the waveguide and scrambling-block cladding materials and methods should be undertaken to ascertain the effects of the present materials upon coupler performance, to identify other likely cladding materials, and to develop more suitable methods of applying the cladding to keep it from flowing after application.

2. Analysis of the deposited reflective materials should be undertaken to assure satisfactory performance of the mirrored interfaces on the waveguide prisms and scrambling block.

3. Precision manufacturing methods should be developed to minimize loss due to mechanical tolerance buildup.

4. A connector should be developed that would ensure the aperture matching of cable and waveguide as well as eliminate connector degradation caused by abrasion during plug insertion.

APPENDIX A

LABORATORY DATA

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Coupler Serial No.	1
Number of Ports	16
1/n	.0625
1-1/n	.9375

READE: $T^* \times 10^{-3}$
$V \times 10^{-3}$
$T \times 10^{-4}$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	T*
1	-	173	142	164	136	142	101	120	167	151	210	182	145	195	109	161	229
2	176	-	182	167	176	139	170	139	200	192	214	179	154	204	126	192	261
3	142	179	-	142	126	129	120	120	173	158	170	145	142	182	110	167	221
4	158	172	142	-	148	139	145	120	173	176	170	167	151	214	126	195	240
5	134	188	129	151	-	120	110	123	179	158	161	145	120	151	114	169	215
6	139	145	134	139	123	-	117	98	148	145	148	142	107	151	95	154	199
7	120	192	145	173	126	139	-	139	182	167	182	161	134	188	101	148	229
8	123	134	123	120	123	95	123	-	145	134	139	134	117	164	95	129	250
9	173	214	188	182	179	148	167	154	-	209	158	188	126	214	107	192	260
10	151	198	167	173	158	142	151	139	200	-	185	145	142	170	112	151	239
11	192	207	173	167	167	139	161	136	164	185	-	173	134	207	101	182	249
12	170	192	148	170	148	139	142	134	182	145	164	-	148	173	114	145	231
13	167	192	173	173	137	120	145	136	145	164	145	167	-	192	95	176	233
14	185	217	192	217	158	148	170	164	207	167	214	170	185	-	142	173	270
15	123	151	142	142	126	104	107	98	117	134	117	129	98	154	-	139	188
16	167	223	188	217	179	161	145	142	210	167	217	167	185	198	151	-	272
V	625	600	640	553	687	640	594	598	557	657	539	686	529	705	629	661	

T_{avg}	.0158
T^*_{avg}	.237
V_{max}	.529
$V_{coupler}$	.426

Coupler Serial No.	2	READ:	$T^* \times 10^{-3}$
Number of Ports	16		$V \times 10^{-3}$
1/n	.0625		$T \times 10^{-4}$
1-1/n	.9375		

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	T*
1	-	120	165	190	120	215	155	150	120	135	215	245	205	220	220	210	269
2	120	-	150	145	120	160	145	120	90	95	170	175	155	165	160	150	212
3	150	140	-	165	110	195	140	150	160	180	190	200	200	210	215	195	260
4	180	120	150	-	130	215	190	180	150	165	170	205	185	220	215	210	269
5	125	120	170	140	-	130	110	120	110	120	150	160	120	120	140	130	191
6	220	170	195	210	130	-	190	165	160	180	225	210	170	190	220	205	284
7	160	155	155	190	105	180	-	125	140	165	200	220	165	190	145	140	244
8	160	120	150	180	110	155	110	-	120	120	190	180	150	160	130	120	212
9	120	85	165	155	100	160	135	130	-	130	160	185	145	165	155	155	215
10	125	95	170	160	120	165	155	125	120	-	180	175	160	165	175	150	224
11	210	160	190	190	145	230	200	190	160	190	-	235	205	240	220	220	299
12	235	145	200	210	160	240	220	195	185	205	220	-	230	250	250	235	321
13	210	155	200	190	115	160	165	160	145	170	200	230	-	190	200	195	269
14	220	160	210	210	120	175	190	165	160	180	230	225	185	-	220	215	287
15	225	170	220	220	140	210	140	125	155	185	220	250	190	220	-	170	284
16	210	160	200	215	130	200	130	120	160	170	225	240	190	220	175	-	275
	510	500	682	636	625	542	500	615	486	585	652	640	522	480	520	510	

T_{avg}	.0171
T^*_{avg}	.257
V_{max}	.480
$V_{coupler}$	.340

Coupler Serial No. 3
Number of Ports 9
1/n 0.11
1-1/n 0.89

READ: $T \times 10^{-3}$
$T^* \times 10^{-3}$
$V \times 10^{-2}$

	1	2	3	4	5	6	7	8	9	T*
1	-	44	42	35	42	38	41	47	39	328
2	46	-	39	40	43	40	41	43	36	328
3	42	40	-	34	40	35	35	42	46	304
4	41	41	30	-	35	34	35	38	31	285
5	41	40	36	31	-	38	37	43	36	302
6	42	40	35	32	40	-	28	42	34	293
7	41	40	34	34	39	33	-	38	31	290
8	50	44	44	40	46	42	30	-	39	335
9	39	38	34	30	39	34	32	39	-	285
V	78	86	68	75	76	78	68	81	67	

T_{avg} .038
T^*_{avg} .305
V_{max} .67
$V_{coupler}$ .60

Coupler Serial No. 4
Number of Ports 9
1/n 0.11
1-1/n 0.89

READ: $T \times 10^{-3}$
$T^* \times 10^{-3}$
$V \times 10^{-2}$

	1	2	3	4	5	6	7	8	9	T*
1	-	48	39	39	52	41	42	48	40	349
2	42	-	37	38	45	45	44	36	41	320
3	37	39	-	34	42	38	33	39	34	296
4	39	40	32	-	40	34	34	40	34	293
5	45	42	35	34	-	39	38	41	40	314
6	46	45	37	35	46	-	40	45	39	333
7	40	40	33	35	44	41	-	42	35	310
8	44	43	39	41	47	46	42	-	41	298
9	38	39	33	34	41	39	35	39	-	298
V	82	81	82	83	77	74	75	75	83	

T_{avg} .039
T^*_{avg} .312
V_{max} .74
$V_{coupler}$ .61

Coupler Serial No.	6	READ:	$T \times 10^{-3}$
Number of Ports	9		$T^* \times 10^{-3}$
1/n	0.11		$V \times 10^{-2}$
1-1/n	0.89		

	1	2	3	4	5	6	7	8	9	T*
1	-	33	33	31	24	25	30	32	31	239
2	31	-	27	32	22	25	28	25	24	214
3	32	29	-	36	27	28	31	31	30	244
4	29	30	34	-	17	30	30	32	31	206
5	23	22	26	28	-	23	27	24	22	195
6	25	24	27	30	22	-	29	25	21	203
7	23	23	27	25	21	25	-	24	22	190
8	22	18	23	24	18	20	33	-	27	185
9	27	23	28	30	23	25	23	28	-	217
V	69	54	67	66	63	67	82	75	68	

T_{avg} .026
T^*_{avg} .290
V_{max} .54
$V_{coupler}$ .47

Coupler Serial No.	7	READ:	$T \times 10^{-3}$
Number of Ports	6		$T^* \times 10^{-3}$
1/n	.17		$V \times 10^{-2}$

	1	2	3	4	5	6	T*
1	-	52	56	57	74	74	323
2	50	-	45	57	57	62	271
3	53	43	-	56	63	55	270
4	68	55	58	-	53	55	290
5	73	56	66	53	-	59	307
6	73	59	56	56	59	-	303
V	68	73	68	93	72	74	–

T_{avg} 0.59
T^*_{avg} .294
V_{max} .68
$V_{coupler}$ .58

Coupler Serial No. 8 READ: $T \times 10^{-3}$
Number of Ports 6 $T^* \times 10^{-3}$
1/n .17 $V \times 10^{-2}$
1-1/n .83

	1	2	3	4	5	6	T*
1	-	49	50	55	47	61	62
2	51	-	45	48	37	54	235
3	47	42	-	45	39	48	221
4	56	48	46	-	42	54	246
5	49	40	41	42	-	48	220
6	62	54	47	51	45	-	259
V	76	74	82	76	79	79	

T_{avg} .048
T^*_{avg} .241
V_{max} .74
$V_{coupler}$ .65

Coupler Serial No. 9 READ: $T \times 10^{-3}$
Number of Ports 6 $T^* \times 10^{-3}$
1/n .17 $V \times 10^{-2}$
1-1/n .83

	1	2	3	4	5	6	T*
1	-	60	43	38	63	48	252
2	57	-	45	44	56	55	257
3	45	46	-	32	49	38	210
4	40	42	31	-	41	32	185
5	61	50	51	41	-	51	254
6	47	52	36	31	51	-	217
V	65	70	61	70	65	58	-

T_{avg} .046
T^*_{avg} .230
V_{max} .58
$V_{coupler}$ .51

Coupler Serial No.	10
Number of Ports	9
1/n	0.11
1-1/n	0.89

READ: $T \times 10^{-3}$
$T^* \times 10^{-3}$
$V \times 10^{-2}$

	1	2	3	4	5	6	7	8	9	T*
1	-	29	17	26	32	33	30	36	35	238
2	25	-	13	35	33	28	34	35	30	233
3	15	12	-	17	14	10	16	14	12	110
4	27	36	20	-	26	26	26	35	33	203
5	34	33	15	25	-	20	33	32	28	220
6	32	28	11	25	20	-	30	27	21	194
7	29	33	18	26	33	31	-	28	27	225
8	34	34	15	33	32	26	27	-	22	223
9	35	29	13	33	28	22	26	23	-	209
V	43	33	55	48	42	33	47	39	34	

T_{avg} .0257
T^*_{avg} .206
V_{max} .33
$V_{coupler}$ .27

Coupler Serial No.	11
Number of Ports	6
1/n	.17
1-1/n	.83

READ: $T \times 10^{-3}$
$T^* \times 10^{-3}$
$V \times 10^{-2}$

	1	2	3	4	5	6	T*
1	-	50	44	40	73	55	262
2	47	-	37	56	40	50	230
3	41	36	-	56	62	34	229
4	39	56	56	-	47	33	231
5	68	39	62	46	-	37	253
6	57	50	35	32	37	-	211
	57	70	56	57	51	60	-

T_{avg} .047
T^*_{avg} .236
V_{max} .51
$V_{coupler}$ .44

Coupler Serial No. 12
Number of Ports 6
1/n .17
1-1/n .83

READ: $T \times 10^{-3}$
$T^* \times 10^{-3}$
$V \times 10^{-2}$

	1	2	3	4	5	6	T*
1	-	30	41	43	40	38	192
2	32	-	42	36	43	38	191
3	40	40	-	41	43	43	207
4	43	36	43	-	45	38	205
5	40	42	44	43	-	34	203
6	37	26	42	26	32	-	163
	74	62	93	60	71	79	-

T_{avg} .039
T^*_{avg} .193
V_{max} .60
$V_{coupler}$ .58

Coupler Serial No. 13
Number of Ports 6
1/n .17
1-1/n .83

READ: $T \times 10^{-3}$
$T^* \times 10^{-3}$
$V \times 10^{-2}$

	1	2	3	4	5	6	T*
1	-	50	55	47	54	46	252
2	48	-	49	35	50	39	271
3	50	47	-	44	51	46	238
4	45	36	45	-	45	34	205
5	44	48	51	42	-	43	228
6	41	38	44	32	43	-	198
	82	72	80	68	80	74	-

T_{avg} .045
T^*_{avg} .223
V_{max} .68
$V_{coupler}$ .58

Coupler Serial No.	14	READ:	$T \times 10^{-3}$
Number of Ports	6		$T^* \times 10^{-3}$
1/n	.17		$V \times 10^{-2}$
1-1/n	.83		

	1	2	3	4	5	6	T*
1	-	46	47	56	56	48	253
2	47	-	38	42	40	36	203
3	49	41	-	47	44	40	221
4	57	50	49	-	51	44	251
5	58	45	47	51	-	42	243
6	51	44	45	46	42	-	228
V	81	82	77	75	75	75	-

T_{avg}	.046
T^*_{avg}	.233
V_{max}	.75
$V_{coupler}$	.62

Coupler Serial No.	15	READ:	$T \times 10^{-3}$
Number of Ports	6		$T^* \times 10^{-3}$
1/n	.17		$V \times 10^{-2}$
1-1/n	.83		

	1	2	3	4	5	6	T*
1	-	66	48	61	61	64	300
2	68	-	52	64	51	63	298
3	51	54	-	51	50	54	260
4	61	67	49	-	50	60	296
5	58	52	47	58	-	59	274
6	63	64	52	60	61	-	300
	75	79	90	79	82	92	-

T_{avg}	.058
T^*_{avg}	.288
V_{max}	.75
$V_{coupler}$	.69